T2K results and prospects

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Neutrino physics

$$U_{\mathrm{PNMS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{-\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Neutrino flavor eigenstates are not identical to mass eigenstates, consequence ν oscillations and non zero ν masses
- Is CP conserved or violated?
- What is the ν mass ordering?
- Are there only 3 ν types?

θ_{23}=50.6+-1.7°

θ_{12}=33.6+-0.80°

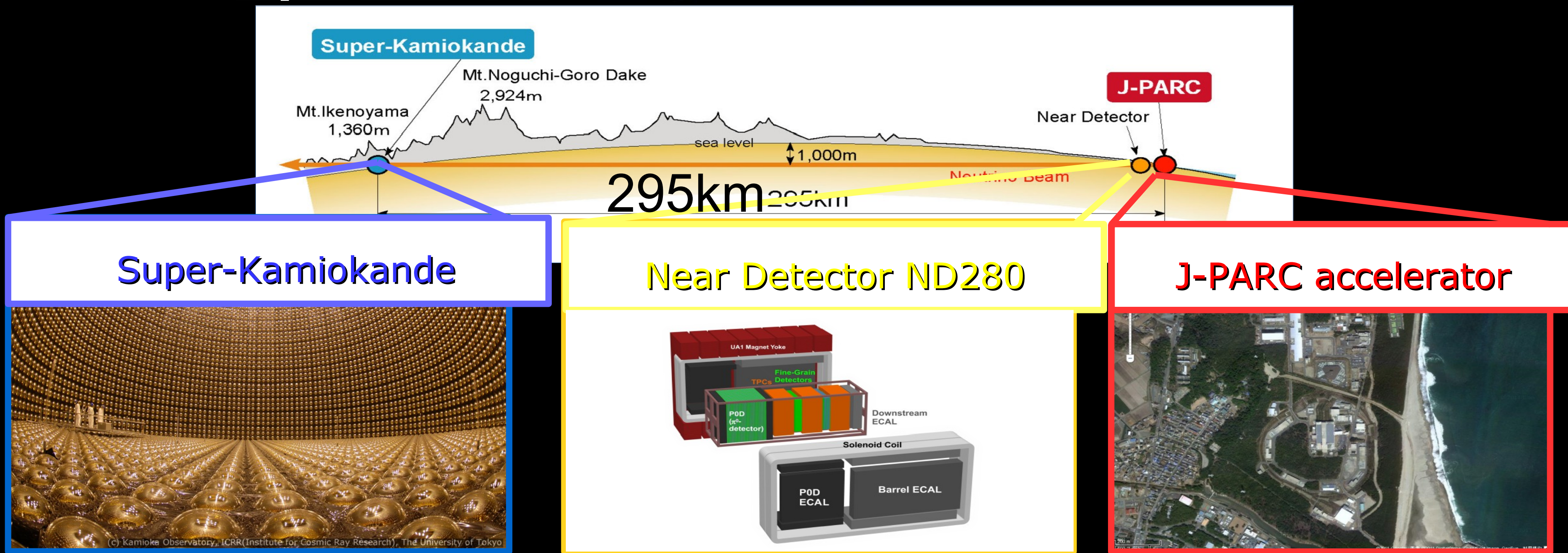
θ_{13}=8.37+-0.15°

Δm^2_{21}=7.53+-0.18x10-15eV^2

$|\Delta m^2_{32}|$=2.51+-0.05x10-3eV^2

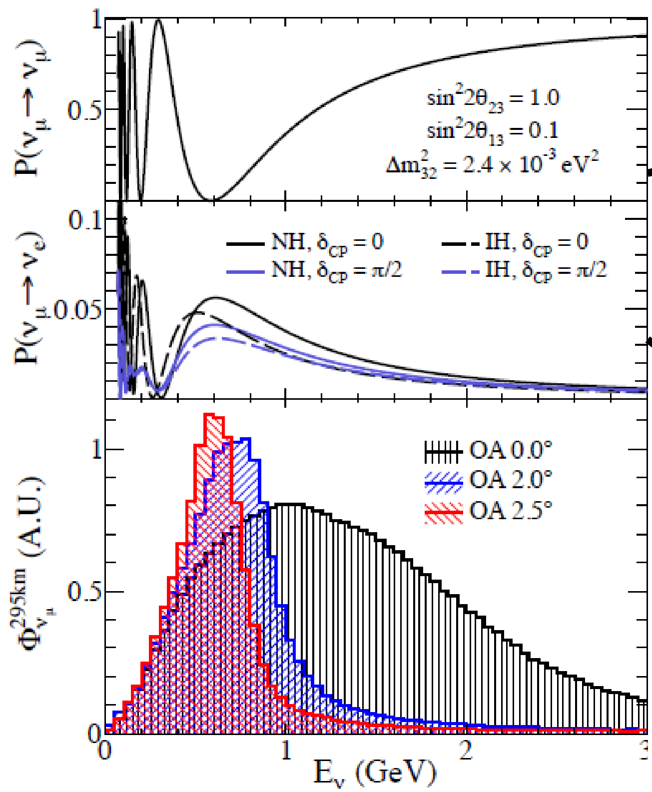
δ_{CP}=?

T2K experiment

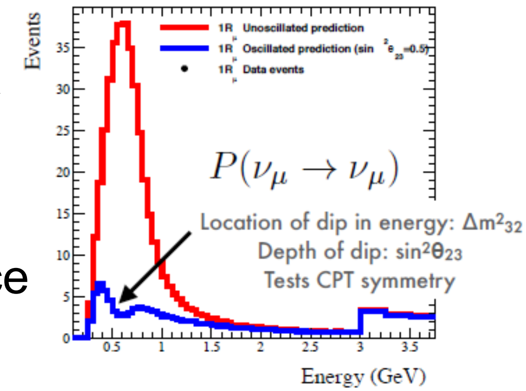


- 2.5° off-axis beam of ν_μ or $\bar{\nu}_\mu$ produced by J-PARC accelerator
- Near Detector located 280 m from ν source:
  - Constrains systematic errors for ν flux
  - Measures ν cross-sections
- Super-Kamiokande far detector located 295 km from J-PARC:
  - 50 kt water Cerenkov detector filled with ultra-pure water
  - Can distinguish ν_μ and ν_e interactions

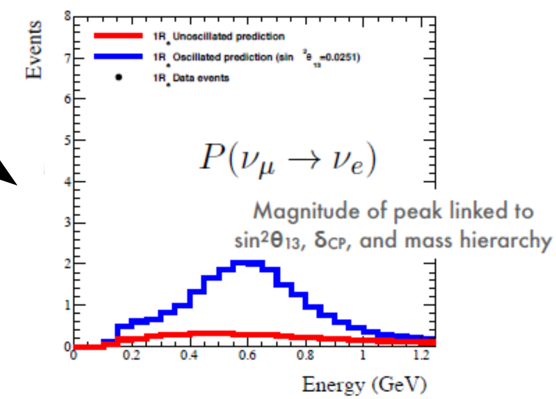
Principles of the T2K ν oscillations



ν_μ disappearance



ν_e appearance



Oscillation probabilities

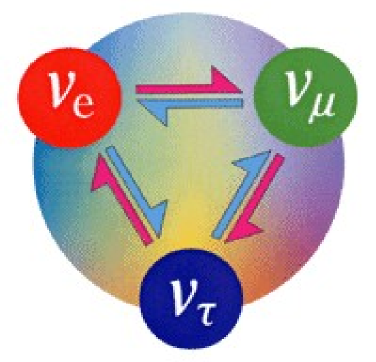
- Long-baseline $\nu_\mu \to \nu_e$ appearance probability depends most strongly on $\sin^2 2\theta_{13}$ and δ_{CP}
  - (But also depends on θ_{23} and other parameters)

$$\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) && \to \text{Leading, matter effect} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} && \to \text{CP conserving} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} && \to \text{CP violating} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21} && \to \text{Solar} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} && \to \text{Matter effect}
\end{aligned}$$

$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij},\ \Phi_{ij} = \Delta m_{ij}^2 L/4E)$

- Long-baseline $\nu_\mu \to \nu_\mu$ disappearance probability depends most strongly on $\sin^2 2\theta_{23}$ and Δm_{32}^2
  - (But degeneracy is broken by $\sin^2 2\theta_{13}$)

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\underbrace{\cos^4\theta_{13} \sin^2 2\theta_{23}}_{\text{Leading Term}} + \underbrace{\sin^2 2\theta_{13} \sin^2\theta_{23}}_{\text{Next-to-Leading}}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$



What's new

- More $\bar{\nu}$ data of ~30%

  $1.12 \times 10^{21} \rightarrow 1.63 \times 10^{21}$ POT

- Update reactor constraints to recent PDG2018 values:

  - Old PDG2016:

    $\sin^2\theta_{13} = 0.0219 \pm 0.0012$
    ($\sin^2 2\theta_{13} = 0.086$)

  - New PDG2018:

    $\sin^2\theta_{13} = 0.0212 \pm 0.008$
    ($\sin^2 2\theta_{13} = 0.083$)

Strategy of oscillation analysis

Predicted ν flux

Cross sections of ν interactions

Fit to near detector data

Near detector systematic uncertainties

Prediction for far detector

Fit to far detector data
Extraction of oscillation parameters

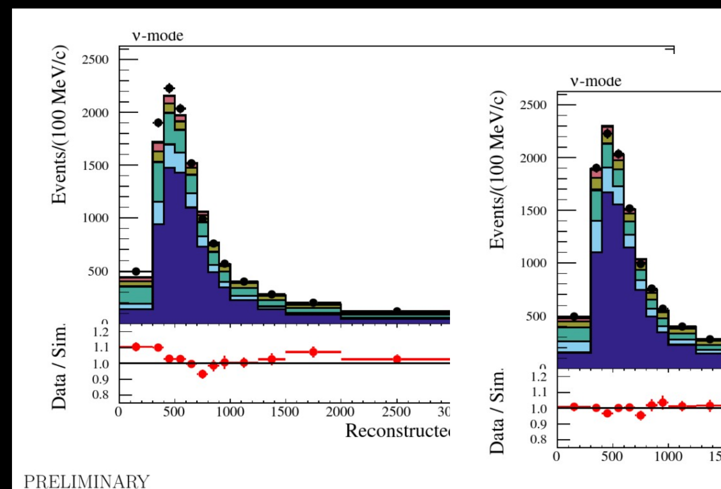
Far detector systematic uncertainties

Near Detector Measurement

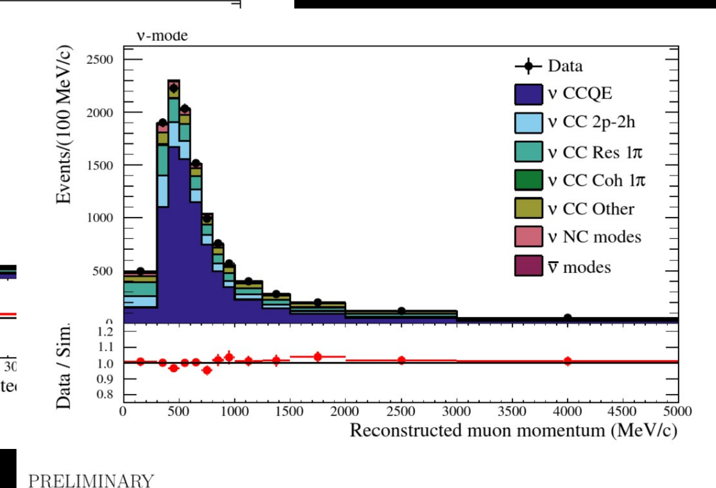
Fit to Near Detector data:

- ν data samples CC-0π, CC-1π, CC-Other
- $\bar{\nu}$ data sample CC-1Track, CC-Ntrack etc.
- Constrain flux and cross-section errors

Pre-fit CC-0π

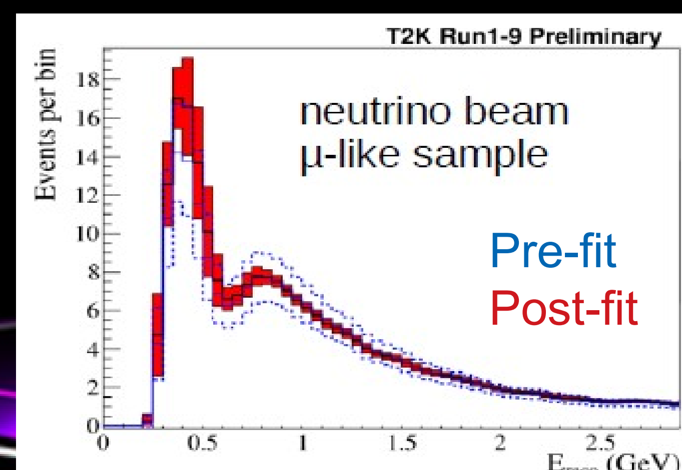


Post-fit CC-0π



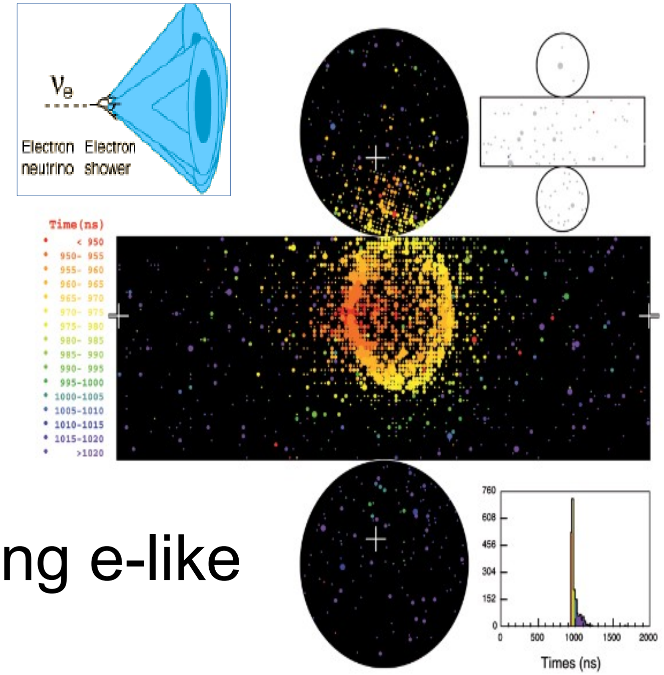
Errors on SK event rate

Sample	w/o ND280	W/ ND280
ν 1Rμ-like	14.6%	5.1%
ν 1Re-like	16.9%	8.8%
$\bar{\nu}$ 1Rμ-like	12.5%	4.5%
$\bar{\nu}$ 1Re-like	14.4%	7.1%

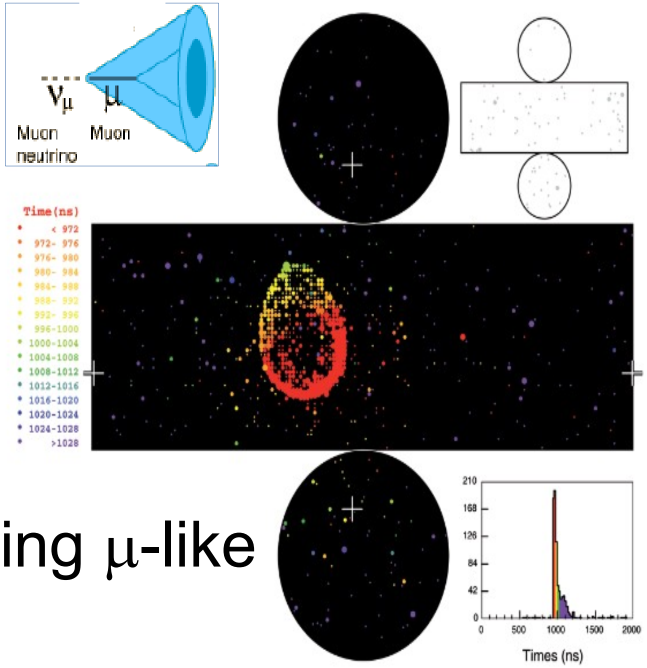


Super-K detection of ν_μ and ν_e

Super-Kamiokande far detector uses Cherenkov light to detect charged particles. It allows to reconstruct particle energy and direction and determine whether its ν_μ or ν_e interacting.



1Ring e-like



1Ring μ-like

T2K data sample

Prediction with: $\sin^2\theta_{13}$=0.0212, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.51x$10^{-3}$$eV^2$, NH

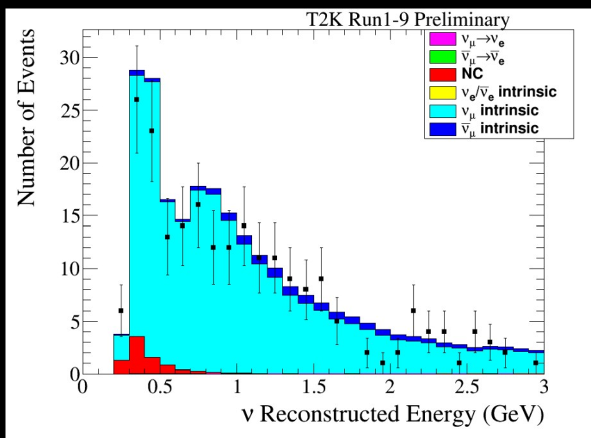
Sample	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=π/2	δ_{CP}=π	Observed
ν 1Rμ-like	272.4	272.0	272.4	272.8	243
$\bar{\nu}$ 1Rμ-like	139.5	139.2	139.5	139.9	140
ν 1Re-like	74.4	62.2	50.6	62.7	75
$\bar{\nu}$ 1Re-like	17.1	19.4	21.7	19.3	15
ν 1Re decay e	7.0	6.1	4.9	5.9	15

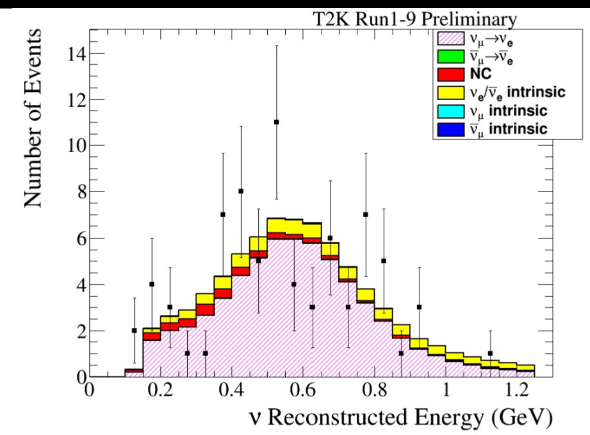
T2K data sample

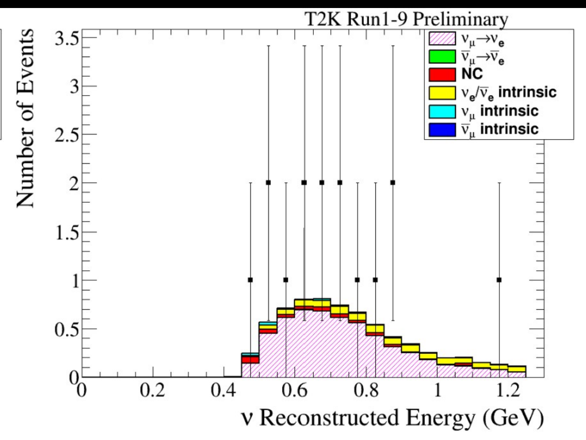
$1.49 \times 10^{21}\ \nu + 1.63 \times 10^{21}\ \bar{\nu}$ POT

1-ring CCQE μ-like | 1-ring CCQE e-like | 1-ring CC-1π e-like

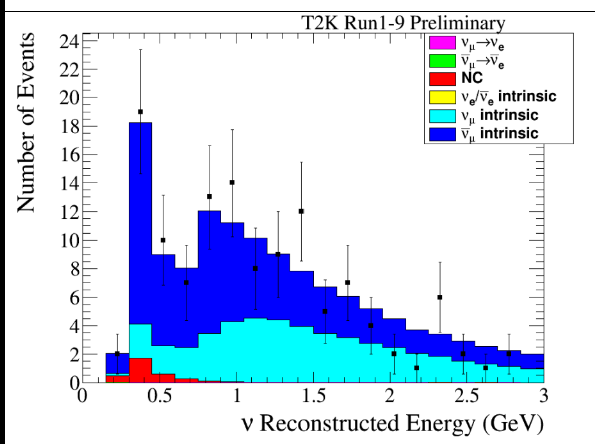
ν

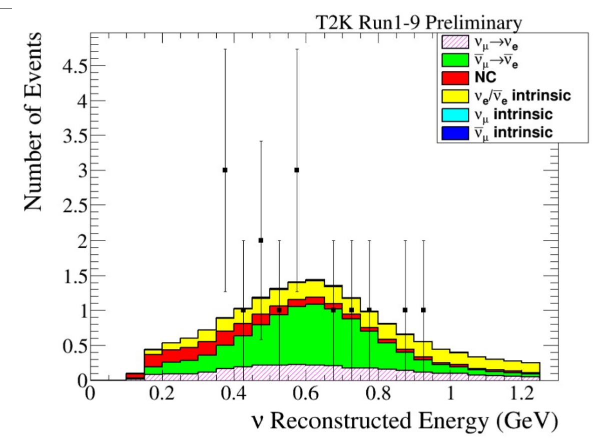






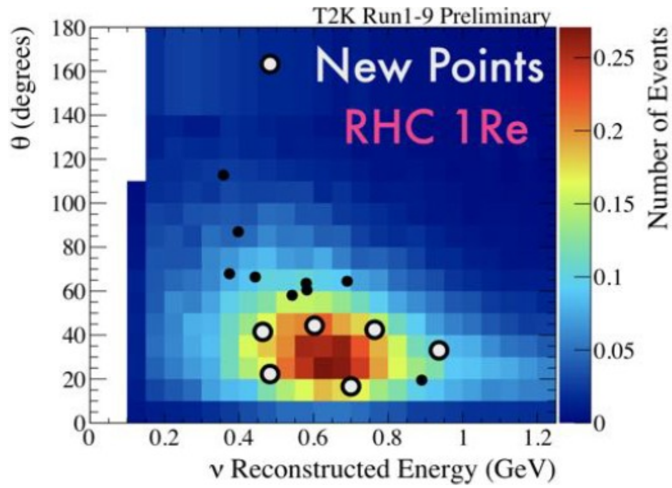
$\bar{\nu}$

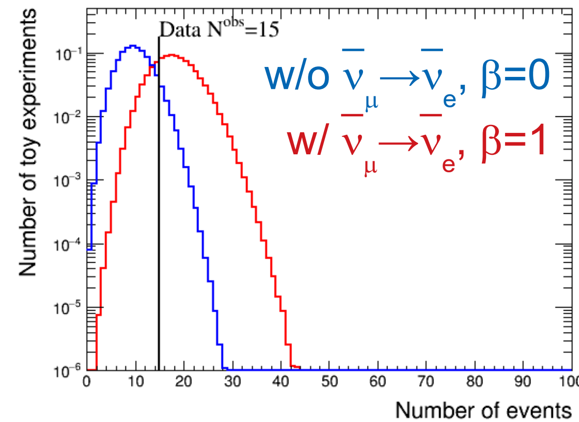




Assuming:
$\delta CP = -\pi/2$
Normal Hierarchy
$\sin^2\theta_{23} = 0.528$
$\sin^2\theta_{13} = 0.0212$

New T2K $\bar{\nu}_e$ appearance results



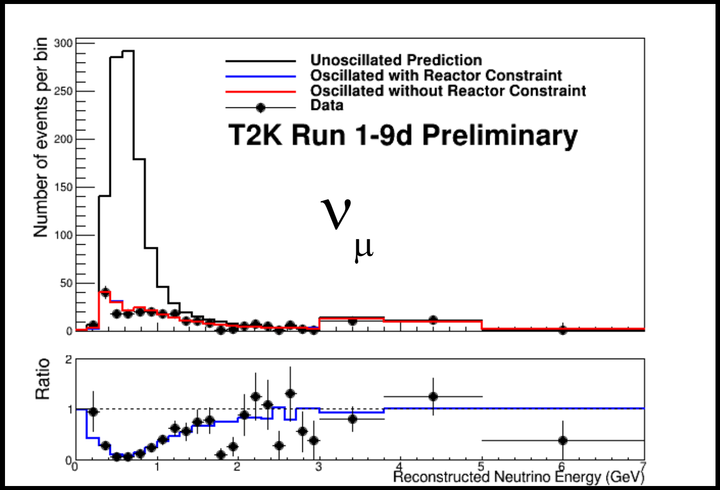


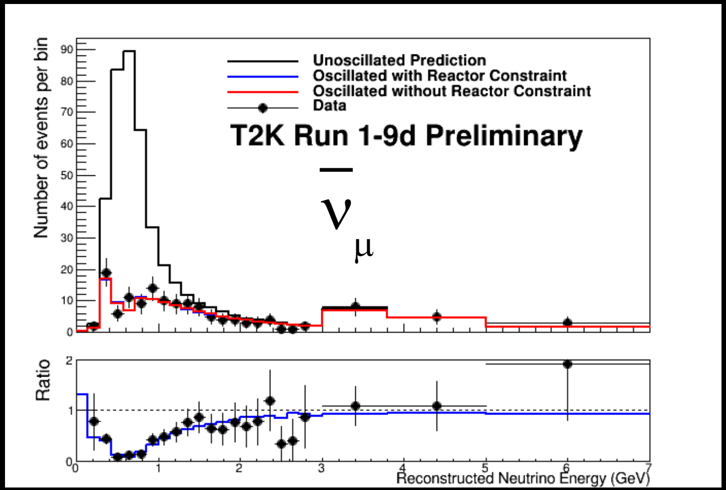
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PNMS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Analysis	P-value β=0 (σ excluded)	P-value β=1 (σ excluded)
Rate only	0.246 (1.82σ)	0.0686 (1.16σ)
Rate+Shape	0.261 (2.25σ)	0.0224 (1.12σ)

- For Rate+Shape no oscillation hypothesis is excluded at 2σ
- More data are needed

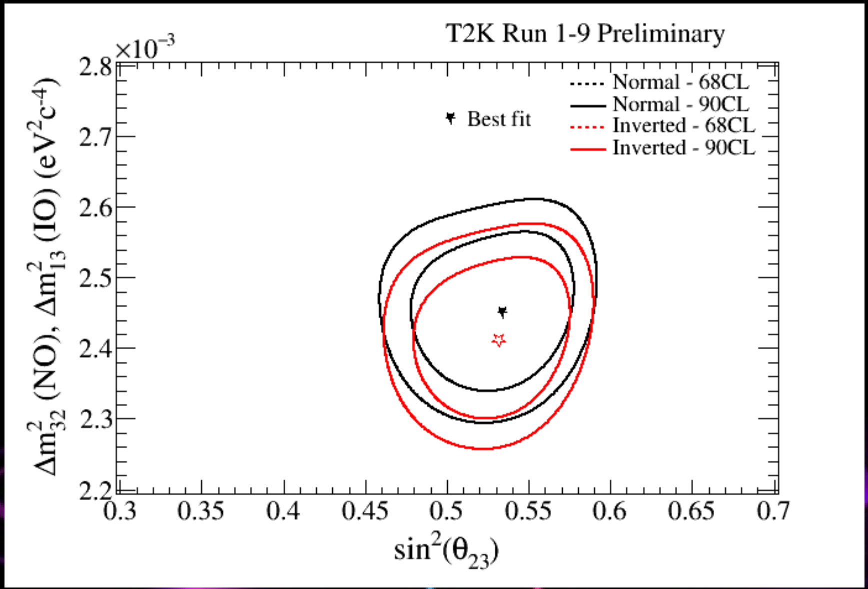
The ν_μ disappearance results





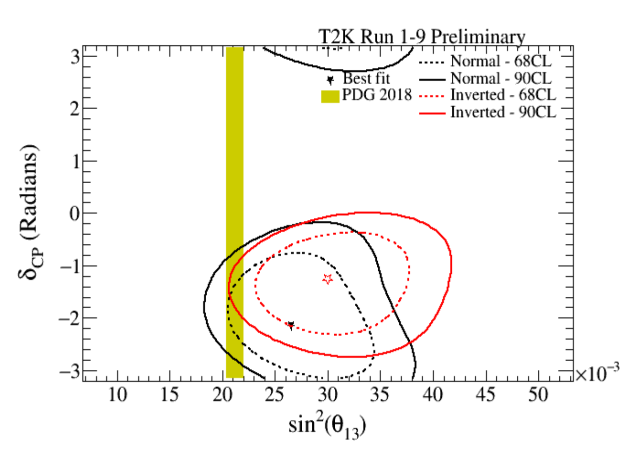
- The best fit point:
  $\sin^2\theta_{23} = 0.532$
  $\Delta m^2_{32} = 2.452\mathrm{x}10^{-3}\mathrm{eV}^2$

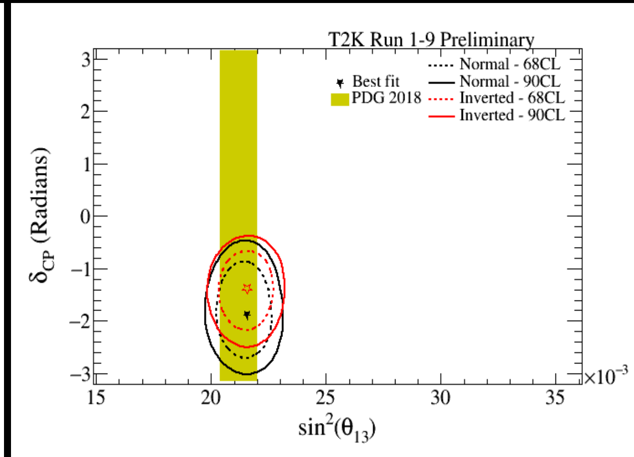
- T2K data are compatible with maximal mixing

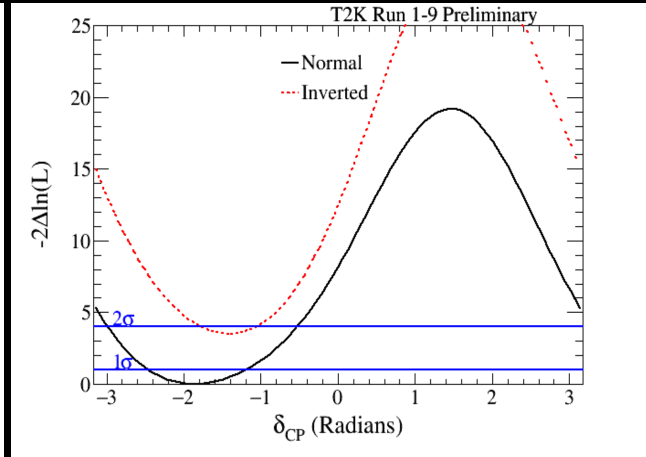


The T2K CP Violation Results

w/o reactor const. w/ reactor const.

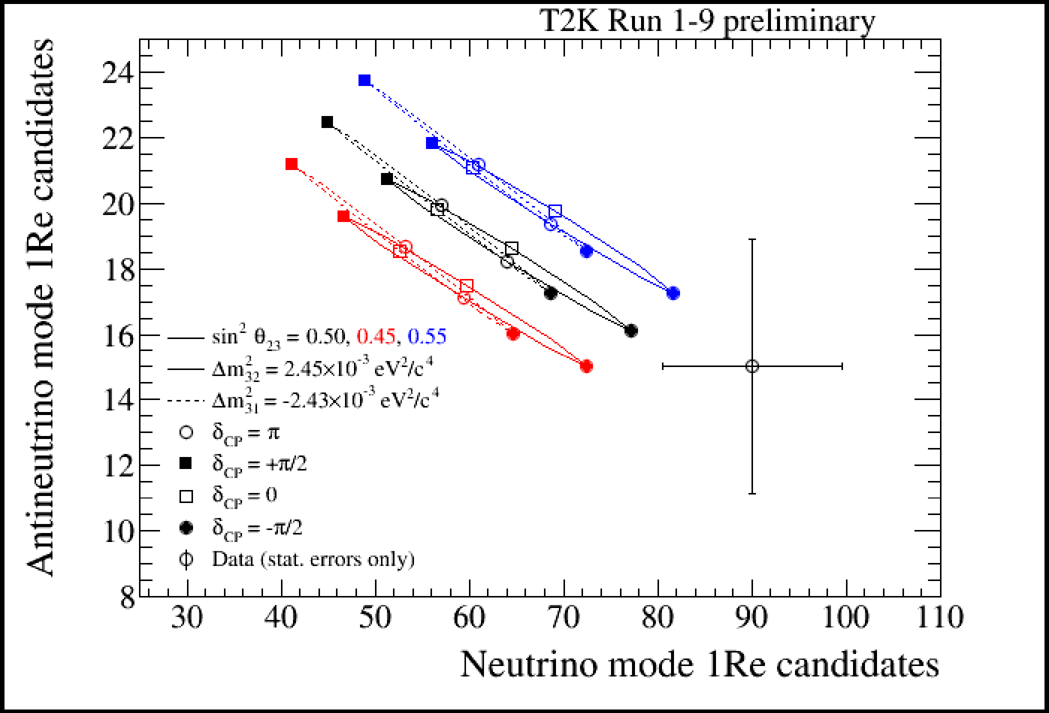




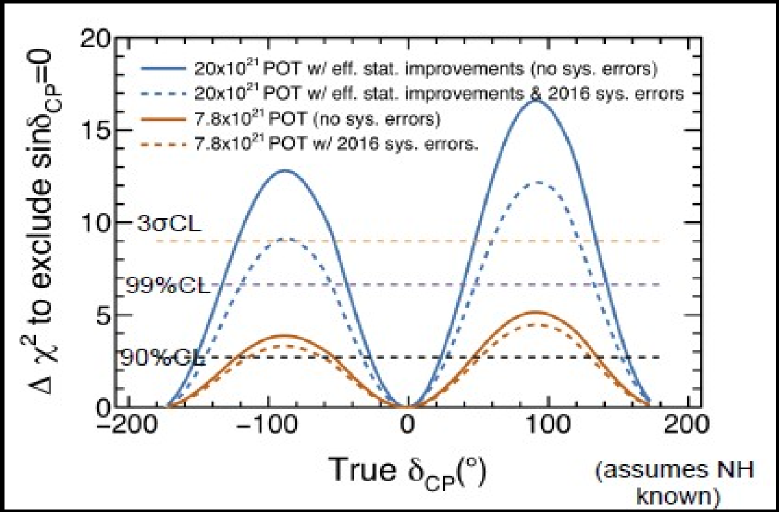


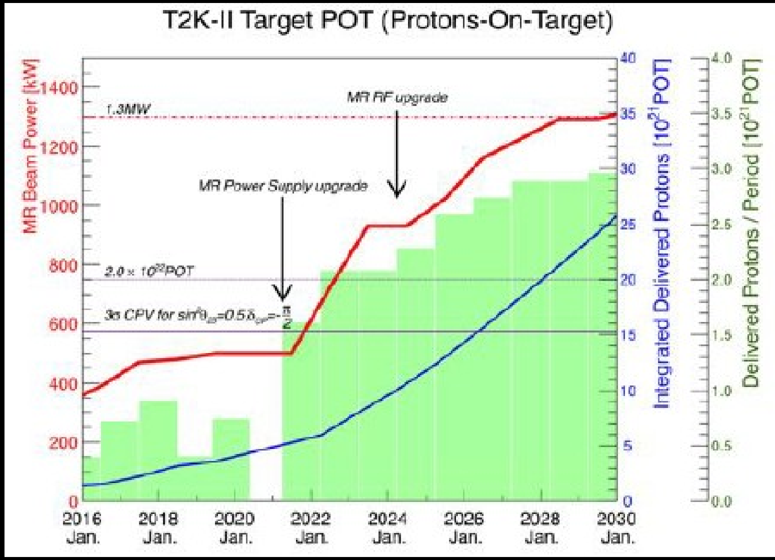
- Preferred value of δ_{CP}=$-\pi/2$ with the best fit point of δ_{CP}=-1.885
- δ_{CP} 2σ intervals:
  - Normal Hierarchy [-2.966, -0.628] radians
  - Inverted Hierarchy [-1.799, -0979] radians
- CP conserving values (δ_{CP}=0 or π) disfavored at 2σ level
- Need more data to reach 3σ result

Probability of $\bar{\nu}_e$ appearance versus ν_e appearance



T2K future prospects

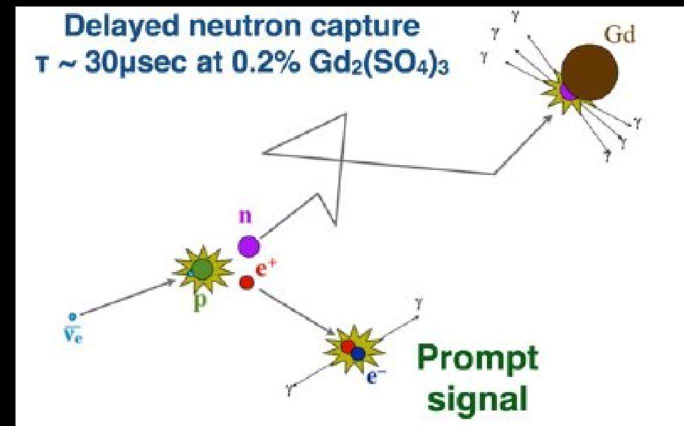




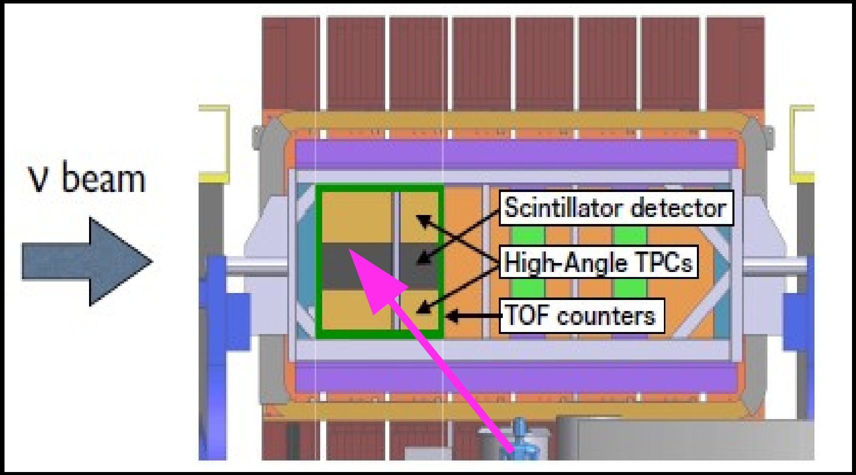
- T2K-II plans to collect 20 x 10^{21} POT by 2027~2028
- May reach 3σ sensitivity to δ_{CP}=0 by ~2026
- Beam line upgrade - expected beam power 1.3 MW
  - -reduce repetition rate 2.48 s→ 1.16 s
  - - more protons per pulse 2.4 → 3.2 x 10^{14}
  - - 320 kA horn current
- Super-K Gadolinium upgrade
- Near Detector upgrade

Super-K Gd upgrade

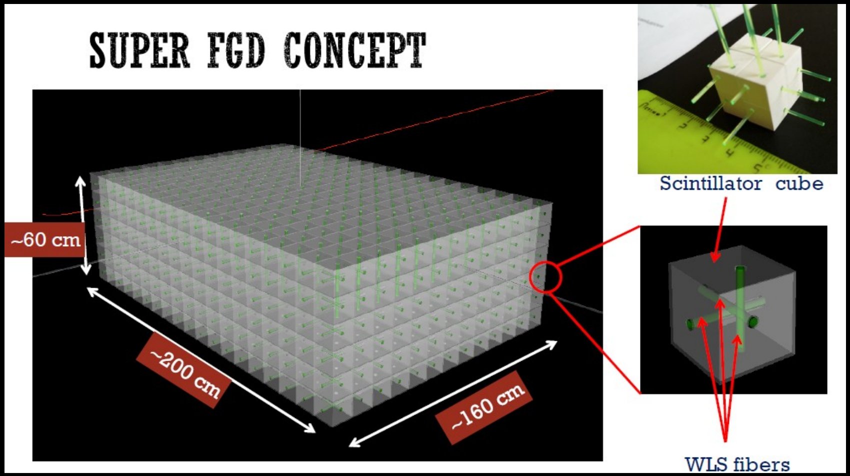
- Super-Kamiokande plans to load Gadolinium to the water tank,
  - 0.02% $Gd_2(SO_4)_3$ by 2019/2020
  - 0.2% later
- Gd can capture thermal neutrons providing delayed gamma signal, so it can tag $\bar{\nu}_e$
- May help $\nu/\bar{\nu}$ discrimination for T2K analysis
- SK tank was drained and opened in summer 2018
- Repairs were done: cleaning, water sealing, tank piping, replacement of dead PMTs
- Tank filling begun in Oct 2018 now tank is almost full.



Near Detector upgrade



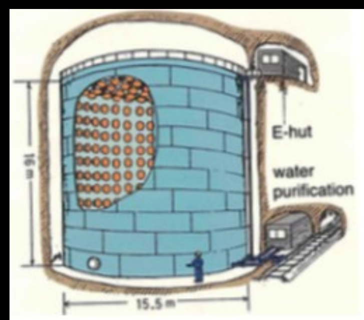
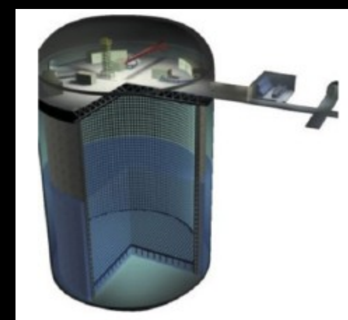
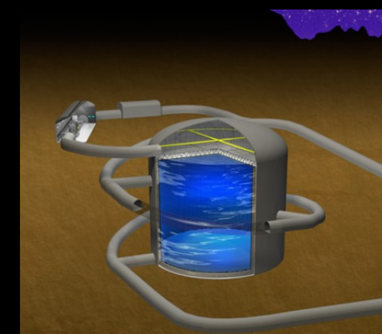
New



- New part composed of scintillator target – SuperFGD, 2 horizontal TPC and TOF detector
- Designed to reduce Near Detector systematic <4%
- Will provide:

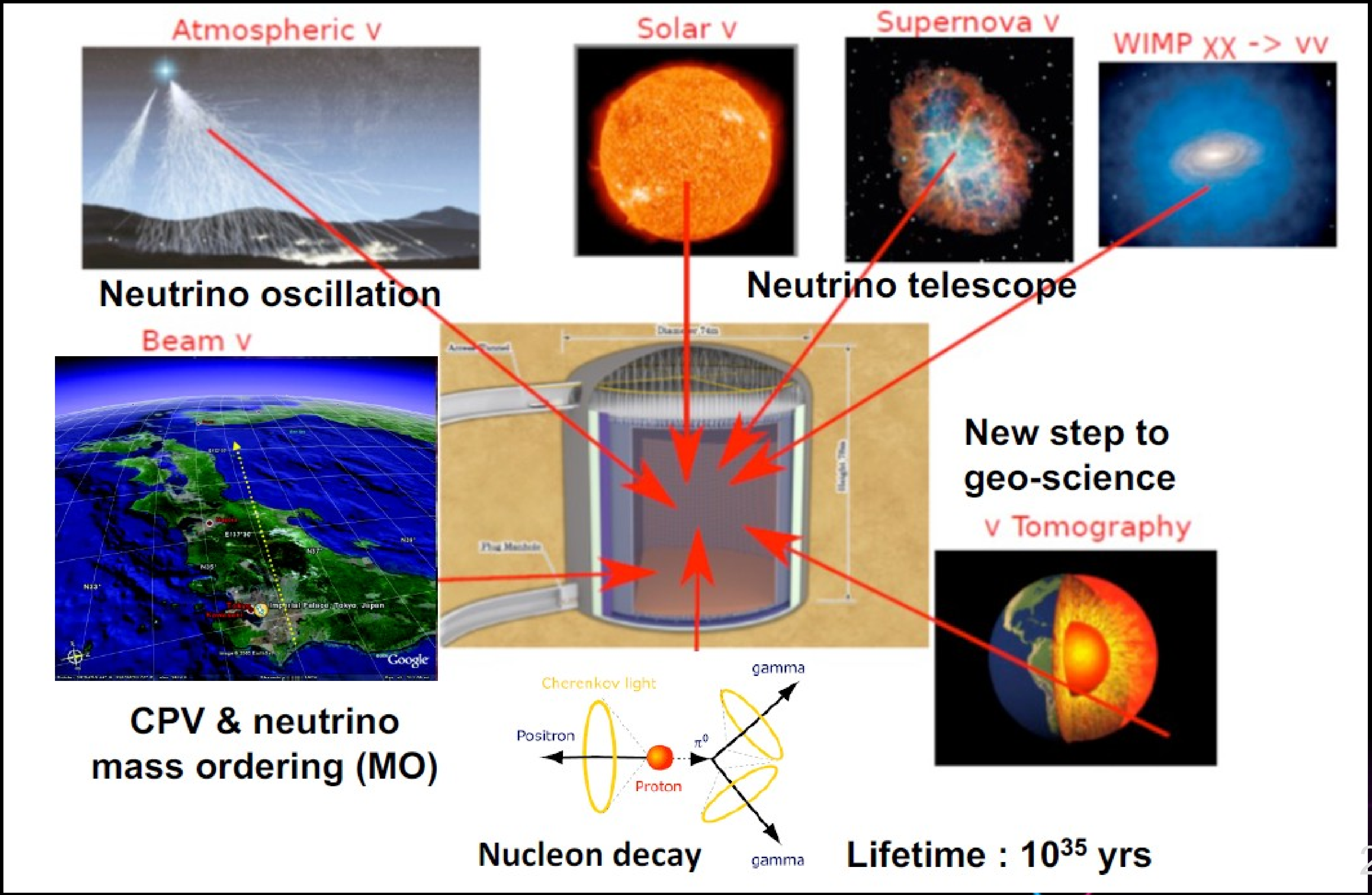
  4π coverage for μ tracks, better short track recon. and good timing
- Beam test were performed at CERN during summer 2018
- Planned to be installed in 2021

Hyper-Kamiokande future project

	Kamiokande 1983-1995	Super-K 1996-	Hyper-K ~2027
Mass (fiducial)	4.5 (0.86) kton	50 (22.5) kton	258 (187) kton
			
PMT, coverage	948 (20%)	11 129 (40%)	40 000 (40%) High QE PMTs

Construction of Hyper-Kamiokande will start in April 2020

Hyper-K physics programe

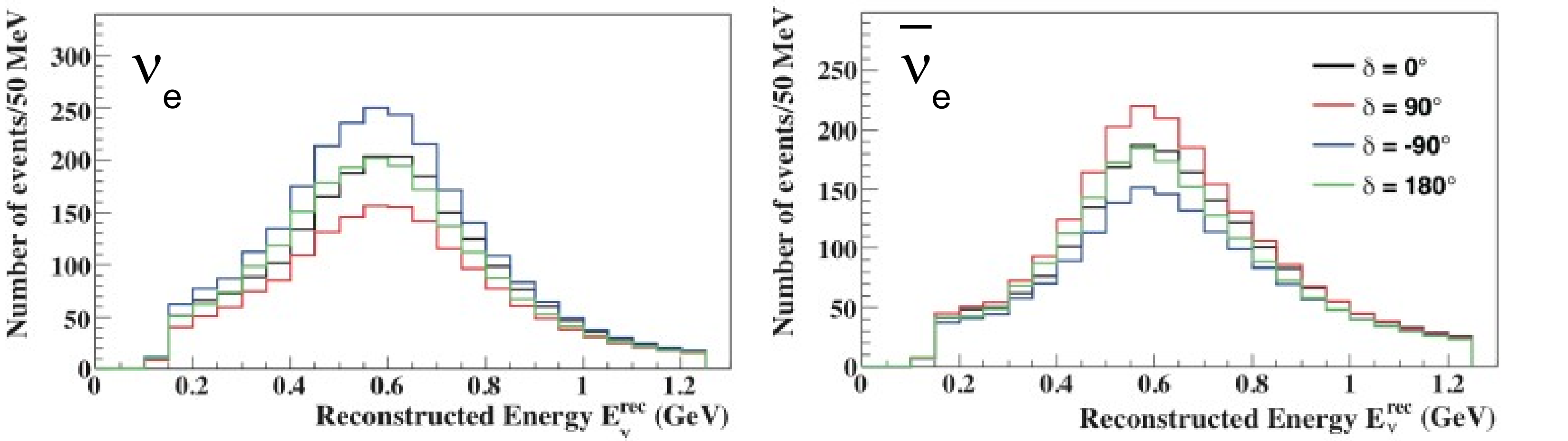


Hyper-K ν beam

High intensity 1.3MW beam directed 2.5° off-axis to Tochibora mine

After 10 years $\nu:\bar{\nu}$ = 1:3

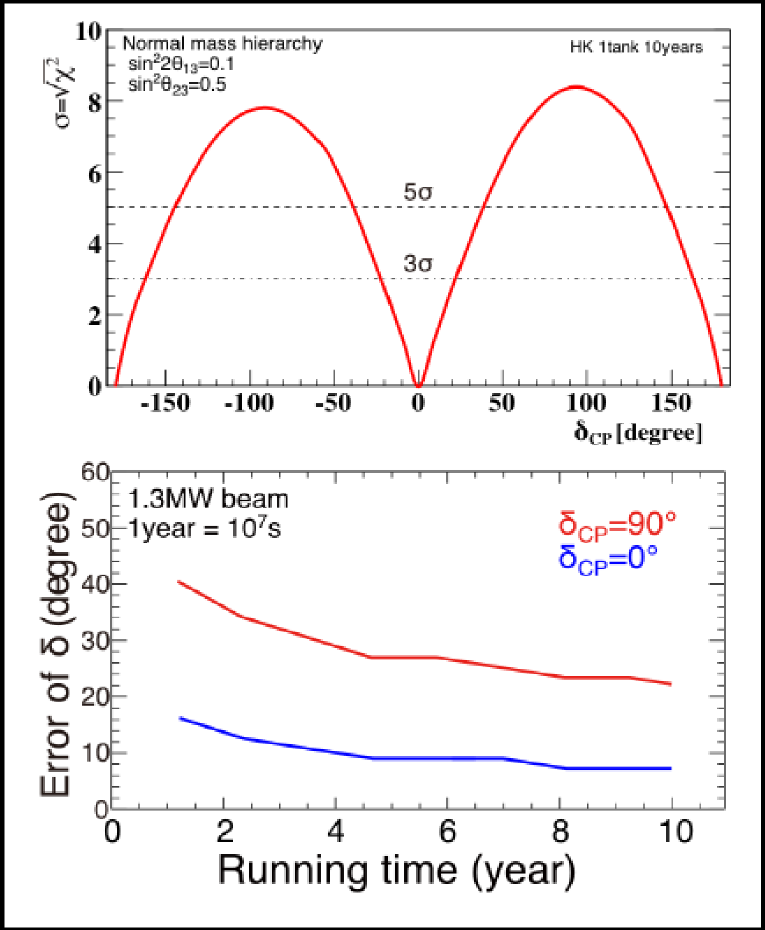
ν_e and $\bar{\nu}_e$ appearance mode



$\delta_{CP} = 0$	Signal $\nu_\mu \to \nu_e CC$	Wrong-sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	Beam $\nu_e/\bar{\nu}_e$	NC	T2K 2018
ν beam	1643	15	7	159	134	75
$\bar{\nu}$ beam	1183	206	4	317	196	9

Hyper-K sensitivity to δ_{CP}

After 10 years $\nu:\bar{\nu}$ = 1:3

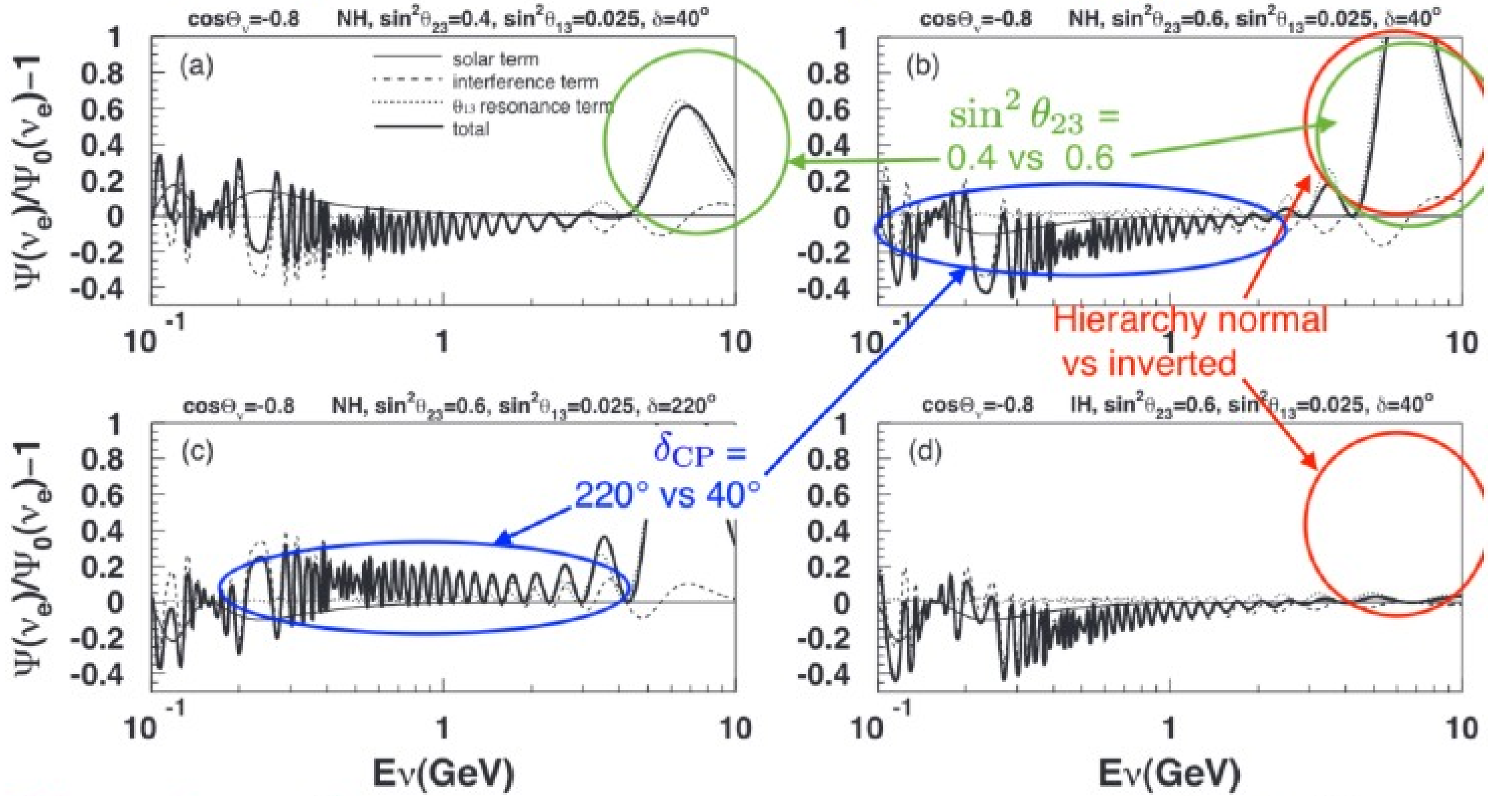


- Exclusion of *sin* δ_{CP} =0:
  - → 76% of coverage of parameter space for CP discovery at 3σ
  - → 58% for 5σ
- δ_{CP} precision measurement:
  - → precision of 22° for δ_{CP}=+-90°
  - → precision of 7° for δ_{CP} = 0° or 180°

Hyper-K atmospheric ν

Contribution of matter effects to $\nu_\mu \rightarrow \nu_e$ oscillation

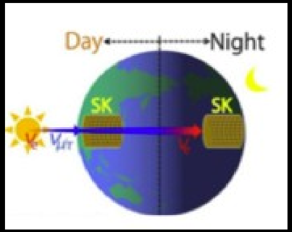
ν_e flux (relative no oscillations) at $\cos\theta_{\mathrm{zenith}} = 0.8$



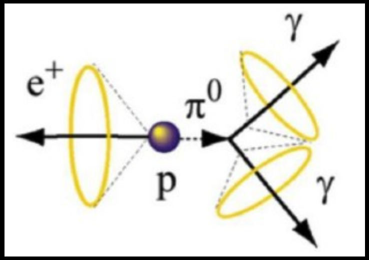
- Mass hierarchy creates resonance in ν_e or $\overline{\nu}_e$ multi-GeV events
- θ_{23} octant sets magnitude of the resonance
- δ_{CP} sets scale/direction of ~1 GeV interference

Hyper-K other measurements

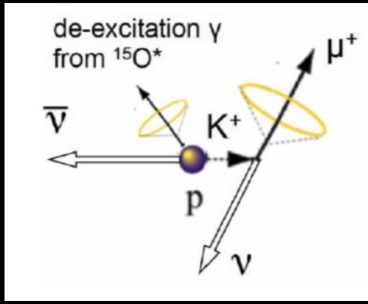
- Combining beam and atmospheric measurements will provide more precise determination of mass hierarchy and determination of θ_{23} octant.
- Detemination of day-night assymetry with 8σ sensitivity after 10 years of operation.



- Detection of neutrinos from Supernovea burst
- Supernovea relic neutrinos
- Current limits for proton decay livetime are at the order of 10^{34} years. Hyper-K will extend those limits to 3σ discovery sensitivity after 20 years:



10^{35} yr



3×10^{34} yr

Summary

- T2k has provided many interesting results
- The analysis of $\bar{\nu}_\mu$ data gives 2σ hint for $\bar{\nu}_e$ appearance
- The CP conserving values of $\delta_{CP} = 0$ and π lie outside of 2σ interval
- Need more data for precise measurements
- It has been proposed to extend T2K run
- Upgrades of various parts of the experiment are undergoing
- Future Hyper-Kamiokande experiment will provide precise measurements in neutrino physics